$X(3872)$, $I^G(J^{PC}) = 0^+(1^{++})$, as the $\chi_{c1}(2P)$ charmonium

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Abstract

Contrary to almost standard opinion that the $X(3872)$ resonance is the $D^{*0}\bar{D}^0 + c.c.$ molecule or the $qc\bar{q}\bar{c}$ four-quark state, we discuss the scenario where the $X(3872)$ resonance is the $c\bar{c} = \chi_{c1}(2P)$ charmonium which "sits on" the $D^{*0}\bar{D}^0$ threshold.

We explain the shift of the mass of the $X(3872)$ resonance with respect to the prediction of a potential model for the mass of the $\chi_{c1}(2P)$ charmonium by the contribution of the virtual $D^*\bar{D} + c.c.$ intermediate states into the self energy of the $X(3872)$ resonance. This allows us to estimate the coupling constant of the $X(7872)$ resonance with the $D^{*0}\bar{D}^0$ channel, the branching ratio of the $X(3872) \to D^{*0}\bar{D}^0 + c.c.$ decay, and the branching ratio of the $X(3872)$ decay into all non-$D^{*0}\bar{D}^0 + c.c.$ states. We predict a significant number of unknown decays of $X(3872)$ via two gluon: $X(3872) \to gluon\ gluon \to hadrons$.

We suggest a physically clear program of experimental researches for verification of our assumption.

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The $X(3872)$ resonance became the first in discovery of the resonant structures XYZ ($X(3872)$, $Y(4260)$, $Z_b^+(10610)$, $Z_b^+(10650)$, $Z_c^+(3900)$), the interpretations of which as hadron states assumes existence in them at least pair of heavy and pair of light quarks in this or that form. Thousand articles on this subject already were published in spite of the fact that many properties of new resonant structures are not defined yet and not all possible mechanisms of dynamic generation of these structures are studied, in particular, the role of the anomalous Landau thresholds is not studied. Anyway, this spectroscopy took the central place in physics of hadrons.

Below we give reasons that $X(3872)$, $I^G(J^{PC}) = 0^+(1^{++})$, is the $\chi_{c1}(2P)$ charmonium and suggest a physically clear program of experimental researches for verification of our assumption.

The two dramatic discoveries have generated a stream of the $D^{*0}\bar{D}^0 + D^0\bar{D}^{*0}$ molecular interpretations of the $X(3872)$ resonance.

The mass of the $X(3872)$ resonance is 50 MeV lower than predictions of the most lucky naive potential models for the mass of the $\chi_{c1}(2P)$ resonance,

$$m_X - m_{\chi_{c1}(2P)} = -\Delta \approx -50\,\mathrm{MeV}, \tag{1}$$

and the relation between the branching ratios

$$BR(X \to \pi^+\pi^-\pi^0 J/\psi(1S)) \sim BR(X \to \pi^+\pi^- J/\psi(1S))\,, \tag{2}$$

that is interpreted as a strong violation of isotopic symmetry.

But the bounding energy is small, $\epsilon_B \lesssim (1 \div 3)$ MeV. That is, the radius of the molecule is large, $r_{X(3872)} \gtrsim (3 \div 5)$ fm $= (3 \div 5) \cdot 10^{-13}$ cm. As for the charmonium, its radius is less one fermi, $r_{\chi_{c1}(2P)} \approx 0.5$ fm $= 0.5 \cdot 10^{-13}$ cm. That is, the molecule volume is $100 \div 1000$ times as large as the charmonium volume, $V_{X(3872)}/V_{\chi_{c1}(2P)} \gtrsim 100 \div 1000$.

How to explain sufficiently abundant inclusive production of the rather extended molecule X(3872) in a hard process $pp \to X(3872) + anything$ with rapidity in the range 2,5 - 4,5 and transverse momentum in the range 5-20 GeV [1]? Really,

$$\sigma(pp \to X(3872) + anything) BR(X(3872) \to \pi^+\pi^- J/\psi) = 5.4\,\mathrm{nb} \tag{3}$$

and

$$\sigma(pp \to \psi(2S) + anything) BR(\psi(2S) \to \pi^+\pi^- J/\psi) = 38\,\mathrm{nb}. \tag{4}$$

But, according to Ref. [2]

$$BR(\psi(2S) \to \pi^+\pi^- J/\psi) = 0.34 \tag{5}$$

while

$$0.023 < BR(X(3872) \to \pi^+\pi^- J/\psi) < 0.066 \tag{6}$$

according to Ref. [3]. So,

$$0.74 < \frac{\sigma(pp \to X(3872) + anything)}{\sigma(pp \to \psi(2S) + anything)} < 2.1. \tag{7}$$

The extended molecule is produced in the hard process as intensively as the compact charmonium. It's a miracle.

As for the problem of the mass shift, Eq. (1), the contribution of the D^-D^{*+} and $\bar{D}^0D^{*0}$ loops, see Fig. 1, into the self energy of the $X(3872)$ resonance, $\Pi_X(s)$, solves it easily.

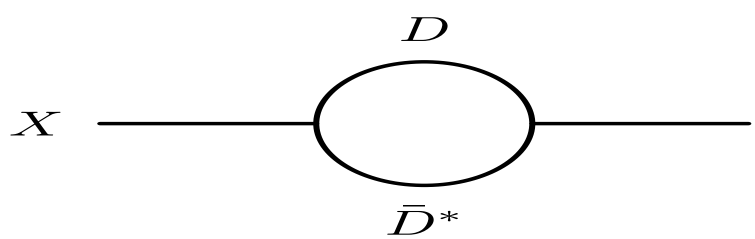

FIG. 1: The contribution of the $\bar{D}^0D^{*0}$ and D^-D^{*+} loops into the self energy of the $X(3872)$ resonance.

$$\Pi_X(s) = \Pi_X^{\bar{D}^0D^{*0}}(s) + \Pi_X^{D^-D^{*+}}(s) = \frac{g_A^2}{8\pi^2}\left(I^{\bar{D}^0D^{*0}}(s) + I^{D^-D^{*+}}(s)\right) , \tag{8}$$

where

$$I^{D\bar{D}^*}(s) = \int\limits_{m_+^2}^{\Lambda^2} \frac{\sqrt{(s'-m_+^2)(s'-m_-^2)}}{s'(s'-s)} ds' \approx 2\ln\frac{2\Lambda}{m_+} - 2\sqrt{\frac{m_+^2-s}{s}}\arctan\sqrt{\frac{s}{m_+^2-s}} , \tag{9}$$

where

$$m_+ = m_{D^*} + m_D\,, \quad m_- = m_{D^*} - m_D\,, \quad s < m_+^2\,, \quad \Lambda^2 \gg m_+^2. \tag{10}$$

For the calculations we use the Lagrangian

$$L(x) = g_A X^\mu \left(D_\mu(x)\bar{D}(x) + \bar{D}_\mu(x)D(x)\right)$$
$$= g_A X^\mu \Big(D^0_\mu(x)\bar{D}^0(x) + \bar{D}^0_\mu(x)D^0(x) + D^+_\mu(x)D^-(x) + D^+_\mu(x)D^-(x)\Big). \qquad (11)$$

The width of the $X \to D^{*0}\bar{D}^0 + c.c.$ decay

$$\Gamma(X \to D^{*0}\bar{D}^0 + c.c.\,,\, s) \approx (g_A^2/8\pi)(2|\vec{k}|/s)\,. \qquad (12)$$

The inverse propagator of the X(3872) resonance

$$D_X(s) = m^2_{\chi_{c1}(2P)} - s - \Pi_X(s) - \imath m_X\Gamma\,, \qquad (13)$$

where $\Gamma = \Sigma\Gamma_i$ is the total width of the $X(3872)$ decays into all $\{i\}$ non-$D^{*0}\bar{D}^0 + c.c.$ channels. According to Refs. [4] and [5] $\Gamma < 1.2$ MeV !

The renormalization of mass [6]

$$m^2_{\chi_{c1}(2P)} - m^2_X - \Pi_X(m^2_X) = 0 \qquad (14)$$

results in

$$\Delta\,(2m_X + \Delta) = \Pi_X(m^2_X) \approx \left(g_A^2/8\pi^2\right) 4\ln(2\Lambda/m_+)\,. \qquad (15)$$

The renormalized propagator has the form [7]

$$D_X(s) = m^2_X - s + \Pi_X(m^2_X) - \Pi_X(s) - \imath m_X\Gamma\,. \qquad (16)$$

If $\Delta = m_{\chi_{c1}(2P)} - m_X \approx 50$ MeV, see Eq. (1) , then $g_A^2/8\pi \approx 0.2$ GeV^2 for $\Lambda = 10$ GeV. According to Ref. [5] such $g_A^2/8\pi$ results in $BR(X \to D^0\bar{D}^{*0} + \bar{D}^0D^{*0}) \approx 0.3$ [8].

Thus, we expect that a number of unknown mainly two-gluon decays of $X(3872)$ into non-$D^{*0}\bar{D}^0 + c.c.$ states are considerable [9]. For details see Ref. [5]. The discovery of these decays would be the strong (if not decisive) confirmation of our scenario.

As for $BR(X \to \omega J/\psi) \sim BR(X \to \rho J/\psi)$, Eq. (2), this could be a result of dynamics. In our scenario the $\omega J/\psi$ state is produced via the three gluons, see Fig. 2.

As for the $\rho J/\psi$ state, it is produced both via the one photon, see Fig. 3, and via the three gluons (via the contribution $\sim m_u - m_d$), see Fig. 2.

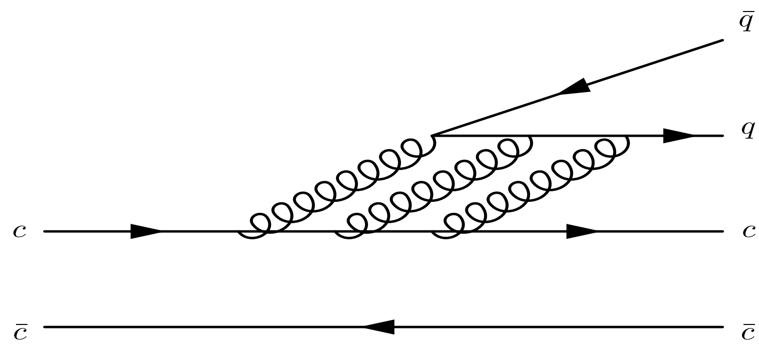

FIG. 2: The three-gluon production of the ω and ρ mesons (via the contribution $\sim m_u - m_d$). All possible permutations of gluons are assumed.

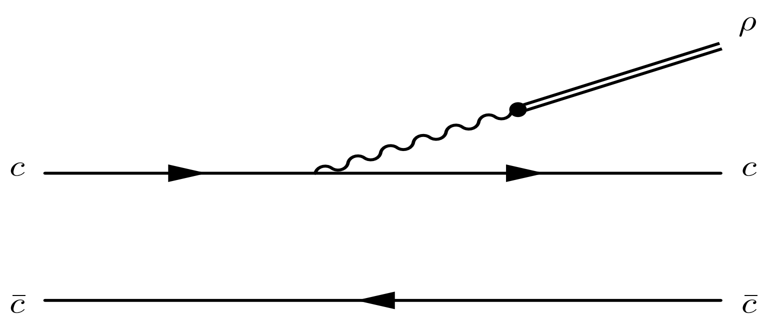

FIG. 3: The one-photon production of the ρ meson. All possible permutations of photon are assumed.

Close to our scenario is an example of the $J/\psi \to \rho\eta'$ and $J/\psi \to \omega\eta'$ decays. According to Ref. [2]

$$BR(J/\psi \to \rho\eta') = (1.05 \pm 0.18) \cdot 10^{-4} \quad \text{and} \quad BR(J/\psi \to \omega\eta') = (1.82 \pm 0.21) \cdot 10^{-4}. \quad (17)$$

Note that in the $X(3872)$ case the ω meson is produced on its tail ($m_X - m_{J/\psi} = 775$ MeV), while the ρ meson is produced on a half.

It is well known that the physics of charmonium ($c\bar{c}$) and bottomonium ($b\bar{b}$) is similar. Let us compare the already known features of X(3872) with the ones of $\Upsilon_{b1}(2P)$.

Recently, the LHCb Collaboration published a landmark result [10]

$$\frac{BR(X \to \gamma\psi(2S))}{BR(X \to \gamma J/\psi)} = C_X \left(\frac{\omega_{\psi(2S)}}{\omega_{J/\psi}}\right)^3 = 2.46 \pm 0.7\,, \quad (18)$$

where $\omega_{\psi(2S)}$ and $\omega_{J/\psi}$ are the energies of the photons in the $X \to \gamma\psi(2S)$ and $BR(X \to \gamma J/\psi)$ decays, respectively.

On the other hand, it is known [2] that

$$\frac{BR(\chi_{b1}(2P) \to \gamma\Upsilon(2S))}{BR(\chi_{b1}(2P) \to \gamma\Upsilon(1S))} = C_{\chi_{b1}(2P)} \left(\frac{\omega_{\Upsilon(2S)}}{\omega_{\Upsilon(1S)}}\right)^3 = 2.16 \pm 0.28\,, \tag{19}$$

where $\omega_{\Upsilon(2S)}$ and $\omega_{\Upsilon(1S)}$ are the energies of the photons in the $\chi_{b1}(2P) \to \gamma\Upsilon(2S)$ and $\chi_{b1}(2P) \to \gamma\Upsilon(1S)$ decays, respectively.

Consequently,

$$C_X = 136.78 \pm 38.89 \tag{20}$$

and

$$C_{\chi_{b1}(2P)} = 80 \pm 10.37 \tag{21}$$

as all most lucky versions of the potential model predict for the quarkonia, $C_{\chi_{c1}(2P)} \gg 1$ and $C_{\chi_{b1}(2P)} \gg 1$.

According to Ref. [2]

$$BR(\chi_{b1}(2P) \to \omega\Upsilon(1S)) = \left(1.63 \pm^{0.4}_{0.34}\right)\%\,. \tag{22}$$

If the one photon mechanism dominates in the $X(3872) \to \rho J/\psi$ decay, see Fig.3, then one should expect

$$BR(\chi_{b1}(2P) \to \rho\Upsilon(1S)) \sim (e_b/e_c)^2 \cdot 1.6\,\% = (1/4) \cdot 1.6\,\% = 0.4\%\,, \tag{23}$$

where e_c and e_b are the charges of the c and b quarks, respectively.

If the three gluon mechanism (its part $\sim m_u - m_d$) dominates in the $X(3872) \to \rho J/\psi$ decay, see Fig.2, then one should expect

$$BR(\chi_{b1}(2P) \to \rho\Upsilon(1S)) \sim 1.6\%\,. \tag{24}$$

We believe that discovery of a significant number of unknown decays of $X(3872)$ into non-$D^{*0}\bar{D}^0 + c.c.$ states and discovery of the $\chi_{b1}(2P) \to \rho\Upsilon(1S)$ decay could decide destiny of X(3872).

Once more, we discuss the scenario where the $\chi_{c1}(2P)$ charmonium sits on the $D^{*0}\bar{D}^0$ threshold but not a mixing of the giant $D^*\bar{D}$ molecule and the compact $\chi_{c1}(2P)$ charmonium, see, for example, Refs. [11], [12], and references cited therein. Note that the mixing of such

states requests the special justification. That is, it is necessary to show that the transition of the giant molecule into the compact charmonium is considerable at insignificant overlapping of their wave functions. Such a transition $\sim \sqrt{V_{\chi_{c1}(2P)}/V_{X(3872)}}$ and a branching ratio of a decay via such a transition $\sim V_{\chi_{c1}(2P)}/V_{X(3872)}$.

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[6] When $(m_{\bar{D}^0} + m_{D^{*0}})^2 < s < (m_{D^+} + m_{D^{*-}})^2$, the renormalization of mass has the form $m^2_{\chi_{c1}(2P)} - m^2_X - Re(\Pi_X^{\bar{D}^0 D^{*0}}(m^2_X)) - \Pi_X^{D^- D^{*+}}(m^2_X) = 0$.

[7] The exact formulae of $Re(\Pi_X(m^2_X)) - \Pi_X(s)$ in all regions of s can be found in Ref. [5].

[8] The assumption of the determining role of the $D^*\bar{D} + c.c.$ channels in the shift of the mass of the $\chi_{c1}(P)$ meson is based on the following reasoning. Let us imagine that D and D^* mesons are light, for example, as the K and K^* mesons. Then the width of $X(3872)$ meson is equal 50 MeV for $g_A^2/8\pi = 0.2 GeV^2$ that much more than the width of its decay into all non-$D^{*0}\bar{D}^0$ channels, $\Gamma < 1.2$ MeV. That is, in our case the coupling of the $X(383)$ meson with the $D^*\bar{D} + c.c.$ channels is rather strong.

[9] Note that in the $\chi_{c1}(1P)$ case the width of the two-gluon decays equals 0.56 MeV [2] that agrees with $\Gamma < 1.2$ MeV satisfactory.

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